A Stable, Single-Frequency RF-Excited Gas Laser at 6328Å

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(Manuscript received April 27, 1965)

A number of 6328Å RF-excited He-Ne lasers have been designed and constructed with special attention to maximizing CW power in a single longitudinal and transverse mode. A single-mode output power of 1.6 mw has been obtained. Some novel features of the cavity structure provide good intrinsic frequency stability. The details of design and operation are given.

I. INTRODUCTION

One of the reasons for the interest in lasers is their potentially very large information bandwidth. Realization of this potential requires, among other things, lasers which oscillate in a single frequency of much improved stability. Since a typical cavity dimension is thousands of wavelengths, lasers are inherently multimode devices. For this same reason, the cavity Q is orders of magnitude greater than the Q for a particular transition, and the laser frequency is determined principally by cavity dimensions. As a result, the precise frequency of a laser oscillator is extremely sensitive to cavity microphonics.

Several techniques have been used to obtain single-mode operation. Javan et al[1] obtained a single axial mode in the first gas laser by reducing gain per pass and maintaining it barely above threshold. Then, of the large number of allowed axial modes, oscillation occurred in only that mode closest to the maximum of the atomic transition. As Javan pointed out, this required very fine control of the excitation to prevent variations in gain. Three-mirror cavities, proposed by Kleinman and Kisliuk[2] and executed by Patel and Koglenik,[3] provide one axial mode even at excitation levels well above threshold. The third mirror varies the frequency dependence of cavity losses and thus aids in the discrimination against all but one mode. However, the addition of a mirror compounds the already serious problem of stabilization of the elementary two-mirror cavity. A sophisticated method for obtaining a single frequency from a

laser in which there is a large number of allowed axial modes was described by Massey et al.[4] A phase modulator within the cavity was operated to give an array of axial modes having the same amplitudes and phases as the sidebands of an FM signal. The output beam was then demodulated, giving a single frequency. They explained that, since this applied to the entire output from a high-power, multimode laser, the technique did not suffer the power loss inherent in other approaches. They obtained an output of 0.1 mw. Once again, however, the addition of components makes the stabilization problem more difficult.

The direct method is to build a two-mirror cavity of such geometry that only one mode exists within the spectral width of the gain even at saturated operation of the laser. This was done first by Gordon and White,[5] using a dc-excited He-Ne 6328Å tube in a cavity about 4 inches long. The gain per pass and axial mode separation in this laser are such that one axial mode at most can oscillate. When the laser containing a single neon isotope is tuned so that the oscillating mode is near the atomic line center, maximum power is reached in that mode. When the cavity length is then detuned by a quarter wavelength, oscillation stops. The present article describes a similar short, single-frequency laser which, however, is RF-excited. The design also incorporates some novel, frequency-stabilizing features.

II. DC VS RF EXCITATION

Dc excitation of gas lasers understandably is the most used technique. Coupling of power is direct; efficient ionization of the gas is sure; and the discharge is maintained without requiring any special attention on the part of the user. However, some dc discharges (although stable on a macroscopic scale) are known to be electrically noisy, and various workers now have observed noise in the output of dc lasers. The amount and character of the noise is variable, but Bolwijn et al[6] have observed noise power as high as 77 db above detector shot noise. Prescott and van der Ziel[7] have demonstrated a correlation between the laser noise and the dc discharge current noise. The variability of the noise is described by Bellisio et al,[8] who occasionally found conditions under which laser noise did not noticeably exceed detector shot noise. Bellisio[9] did not learn how to achieve this quiet condition in a controlled way. Although some workers may have learned ways to reduce the noise in dc lasers, there appears to have been no publication of any technique or theory.

In contrast to dc excitation, RF discharges are characteristically quiet. Both Bellisio et al[8] and Bailey and Sanders[10] found no laser noise significantly above detector shot noise when using RF excitation of the

laser. Paik et al[11] have found that application of RF signals to the anode of dc discharge tubes causes the noise to be replaced by "coherent, noise-free oscillations." The suitability of RF excitation for stable operation of lasers is further suggested by the fact that RF lasers can be operated closer to threshold than can dc lasers.

Since one objective of the present work is to obtain as stable a laser frequency as possible, RF excitation has been used. Capacitive coupling of RF power to the small bore ($\approx$1 mm) discharges required for single-mode operation poses a major technical problem, and its solution will be described.

III. LASER DESIGN: SINGLE FREQUENCY

The laser was designed to oscillate at maximum power in one frequency in a cavity of maximum intrinsic stability. The general approach was similar to that of Gordon and White,[5] and involved building a two-mirror cavity of such geometry that only one axial mode can oscillate. Maximum power, however, required analytical selection of cavity length and mirror transmission.

From the Fabry-Perot condition for resonance, the frequency interval between successive axial modes is $c/2\mu d$, where c is the velocity of light, μ is the index of refraction of the medium, and d is the physical length of the cavity. Clearly, making d arbitrarily small makes the mode separation arbitrarily great. However, as d diminishes, so does the gain per pass at the line center. We want that length which gives maximum absolute difference between the gain of the desired mode, presumed to be located near the line center, and the gain of the adjoining axial mode. Hence, for a low-gain transition (order of ten per cent per meter), we write for the gain of the Doppler-broadened line

$$g(\nu,d) = g_0 d \exp - \left[\frac{\nu - \nu_0}{0.6\Delta\nu_D}\right]^2$$

where g_0 is gain per unit length at line center, d is cavity length, $\nu - \nu_0$ is frequency interval from line center, and $\Delta\nu_D$ is the half-maximum Doppler width. The gain is evaluated at line center and at $\nu - \nu_0 = c/(2\mu d)$ and the difference is maximized. For the 6328Å line in Ne at 450°K, the resultant optimum cavity length is 15 cm. This assumes that gain is uniform from mirror to mirror. For a real cavity, part of whose length must be wasted, the mirror separation is made $16\frac{1}{2}$ cm and the length of gain is $13\frac{1}{2}$ cm.

It is well known that gain, in this type of gas laser, varies inversely with tube diameter. A diameter of 1.2 mm yields an expected g_0 of 20

per cent per meter,[5] or 2.7 per cent in $13\frac{1}{2}$ cm, which is well above dissipative losses. A tube diameter of 1.2 mm gives a Fresnel number of 0.7 in a cavity comprising a flat mirror separated $16\frac{1}{2}$ cm from a one meter-radius spherical mirror. This gives 0.4 per cent diffraction loss per pass in the lowest-order transverse mode, but at least 5 per cent loss per pass in all higher-order modes.[12] Thus, the cavity will support only one transverse mode.

For $d = 16\frac{1}{2}$ cm, $c/(2\mu d) = 900$ mc, and, with one axial mode on the line center, gain at the adjoining axial modes is about 1 per cent. In a cavity designed for minimum loss, these adjoining modes would oscillate. However, when maximum power is desired in an external beam, the procedure is then to increase transmission of one mirror until losses are too great for the adjoining modes. Bennett[13] has reported a calculation by Kompfner and Rigrod of the optimum mirror transmission for maximum coupling out of both (identical) cavity mirrors. They obtain

$$T_{\text{opt}} = \sqrt{GL} - L$$

where G is gain per pass and L is loss per pass. Since maximum power is desired in one beam, and since mirrors now can be made with total losses much smaller than other cavity losses,[14] one mirror is coated for maximum reflectivity. Such mirrors are estimated to reflect at least 99.8 per cent. In the present "round-trip" case, the above expression gives a T_{opt} for the output mirror of about 1 per cent or a little more for a realistic range of estimated losses. The output mirror therefore is coated for 1 per cent transmission.

This design gives a single-frequency laser only if the desired axial mode is close to the line center. If two adjoining modes are arranged symmetrically about the line center, each will have a gain of about 2 per cent and will oscillate. Thus, as the cavity changes length by quarter wavelengths, it drifts between one and two oscillating modes. As another option, the cavity can be made so short that only one axial mode can exist at any instant, but such a cavity would now drift between one and zero oscillating modes. Unless cavity dimensions are held constant to about a quarter wave, the only real choice is between a cavity that oscillates sometimes in two modes and a cavity that sometimes doesn't oscillate. The present approach is to design for maximum power and to stabilize at least well enough to maintain one frequency.

IV. LASER DESIGN: STABILITY

The degree of frequency instability is obtained from the Fabry-Perot condition for resonance, from which it follows that

$$-\frac{\Delta\nu}{\nu} = \frac{\Delta\mu}{\mu} + \frac{\Delta d}{d}$$

where ν is frequency, μ is the index of refraction of the medium, and d is physical length of the cavity. The size of $\Delta\mu/\mu$ depends on the construction of the laser. External-mirror lasers shift in frequency by tens of megacycles as the air within the cavity changes temperature and pressure. Thermal expansion of the frame changes d. A change in temperature of 0.1°C shifts the frequency of the 6328Å laser 1,200 mc on an aluminum frame, 40 mc on an Invar frame, and 20 mc on a frame of fused quartz. Jaseja et al[15] observed that lasers on Invar frames can shift 140 kc by magnetostriction in the earth's field.

Past work on frequency stabilization has centered on acoustic isolation of the laser[16] or the generation of an error signal which is fed back and which corrects the length of the cavity[17-20] against thermal drift. Much less attention seems to have been paid to the stabilily of the structure itself. The effort here has been to construct a laser frame of maximum intrinsic mechanical stability. The cavity, shown in Fig. 1, comprises a flat fused quartz mirror, a perforated tube of fused quartz $1\frac{1}{2}$ inches in diameter and $6\frac{1}{2}$ inches long, and a spherical fused quartz mirror of one meter radius. Each end of the quartz tube is relieved so as to leave three small studs equally spaced around the tube circumference. The lines connecting pairs of studs at opposite ends of the tube are parallel with the tube axis. The stud faces are slightly convex and optically polished. The margins of the mirrors are uncoated, and, when the mirrors are properly installed, optical contact can be observed be-

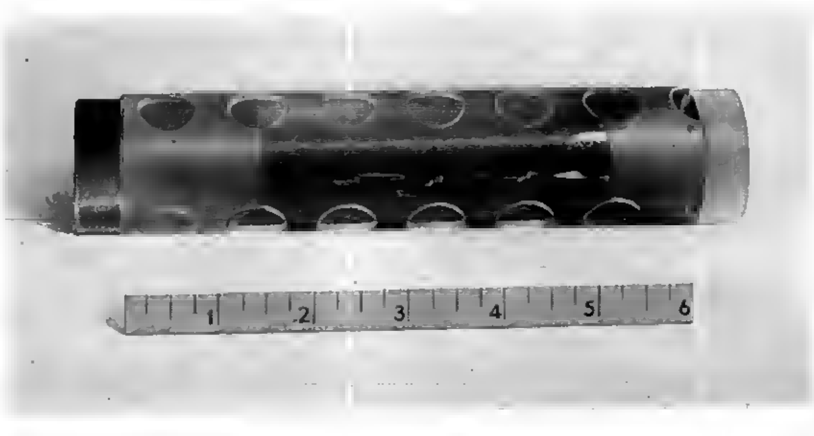

Fig. 1 — The laser cavity, comprising two mirrors and a fused quartz tube which alone determines mirror spacing.

tween mirrors and studs. (A small black spot appears, surrounded by Newton rings.) Ordinarily, mechanical structures contain microscopically rough interfaces. Disturbances of such structures produce jitter in the relative positions of the parts as the actual points of contact are shifted. Such jitter is precluded in the present design. Meissner[21] has observed that passive Fabry-Perot interferometers must follow this design if they are to maintain their adjustment. Some idea of the consequences of this for laser cavities can be gained from realizing that the best resolving power in Meissner's day was the order of 10^7. For an instrument with a resolution of 10^7 to lose its adjustment implies a change in optical frequency of at least tens of megacycles.

The mirrors are held against the ends of the quartz tube; there is no provision for mirror adjustment. The tube is simply made with sufficient care that the optical axis of the installed mirrors is sensibly collinear with the axis of the tube. The discharge tube, shown in Fig. 2, is mounted in the cavity and is then positioned laterally until it is aligned on the cavity axis. The discharge tube is then clamped into position with screws which are mounted on the quartz tube.

Each mirror is backed up by a spring which ensures steady contact between mirror and quartz tube. The spring also decouples the compression of the quartz tube from the supporting structure which uses ordinary, large thermal coefficient materials. The cavity is tuned by adjusting spring compression and hence compression of the quartz tube. Young's modulus and cross section of the tube are such that a force of about 4 pounds tunes the cavity through one axial mode spacing, effectively 900 mc.

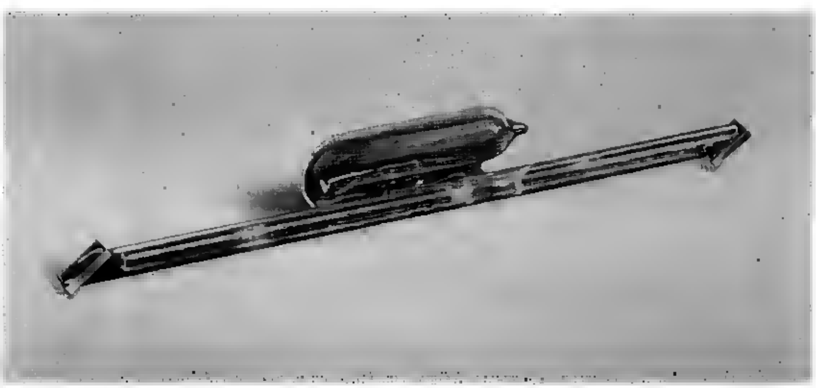

Fig. 2 — The fused quartz discharge tube. The windows are optically contacted. Length is $6\frac{1}{4}$ inches.

These are the essentials of the design. One embodiment of the design is shown in Fig. 3. Most of the materials of the supporting structure are plastic to avoid excessive eddy-current losses. The RF is coupled capacitively with $1\frac{1}{2}$-inch diameter copper rings which are far out of contact with the discharge tube. The rings are actually a snug fit to the inside of the quartz tube of the cavity. When the electrodes are wrapped directly on the outside of the discharge tube, the electric field in the discharge tube near the electrode is large. Bombardment damage is then rapidly produced on the inside wall of the tube, and tube life is much reduced. The life of RF-excited laser tubes appears to be determined by the rate of this damage process.

V. DISCHARGE TUBE

The discharge tube, shown in Fig. 2, is $6\frac{1}{4}$ inches overall. The tube-within-a-tube arrangement (1.2 mm bore inside a 4 mm bore tube) provides the small bore needed for high gain over most of the length, while at the same time leaving a large diameter space at each end which is easily ionized by the RF power. Once the ends are ionized, the small bore section then lights also. A straight tube of 1.2 mm bore can be ionized with capacitive coupling, but only with very large electric fields and hence a large rate of damage.

The body of the tube and windows are of fused quartz. Assembly is accomplished by optically contacting the windows to the optically-polished faces of the tube. Early research with RF-excited gas lasers showed that tube life was severely limited unless the tube was made of

Fig. 3 — One form of the assembled laser. The supporting structure is mostly plastic to avoid eddy-current losses.

fused quartz.[22] The evidence in the literature[23-26] suggests that the reason for this is that the rate of damage in ordinary glasses is orders of magnitude greater than in quartz. Since the tube is entirely of quartz, the dominant source of contamination is the damage process cited above. Tubes of the type shown have had useful lifetimes of hundreds of hours. Getters now are used in the tubes, and greater lifetimes are anticipated.

The tubes are pumped and baked at about 450°C overnight. When the system has cooled and is valved off before filling, the pressure is in the 10^{-9} Torr range. The tubes are filled to 3.0 Torr with a 5/1 ratio of He-Ne gas. Natural abundance gases are used. These tubes, in the cavities described above, routinely radiate about 1 mw in one frequency in a single coherent external beam, and values as large as 1.6 mw have been obtained.

The frequency characteristics of these lasers are now being investigated. It is commonly known that the short-term frequency spread of the oscillation of external mirror gas lasers under laboratory conditions typically is tens, even hundreds, of megacycles. Our preliminary measurements show that this can be reduced to 100 kc or less with the present lasers — even when operated on an optical bench in a second-floor laboratory. Work is continuing to reduce the microphonic sensitivity of these lasers, and further improvements in the frequency spread are expected.

I wish to acknowledge the resourceful, energetic assistance of R. H. Delaney.

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